A Feasibility Study on Crack Identification Utilizing Images Taken from Camera Mounted on a Mobile Robot

AUTHOR(S):

Kim, C.W.; Chang, K.C.; Sasaka, Y.; Suzuki, Y.

CITATION:

Kim, C.W. ...[et al]. A Feasibility Study on Crack Identification Utilizing Images Taken from Camera Mounted on a Mobile Robot. Procedia Engineering 2017, 188: 48-55

ISSUE DATE:

2017

URL:

http://hdl.handle.net/2433/226451

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 188 (2017) 48 – 55

Procedia Engineering

www.elsevier.com/locate/procedia

6th Asia Pacific Workshop on Structural Health Monitoring, 6th APWSHM

A Feasibility Study on Crack Identification Utilizing Images Taken from Camera Mounted on a Mobile Robot

C.W. Kim[a]*, K.C. Chang[a], Y. Sasaka[b], Y. Suzuki[a]

[a]Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8540, JAPAN
[b]Innovation Laboratory, NEC Solution Innovators, Ltd., Tokyo 136-8627, JAPAN

Abstract

Many roadway and highway bridges have been suffering from aging and deterioration problems. To inspect those bridges more efficiently and accurately, the Japanese government launched a series of national projects aiming to develop various innovative robotic inspection systems to support conventional visual inspections. This study is devoted to developing the sensing modules compatible with the robotic inspection system. To preliminarily investigate the feasibility of the image-type sensing modules, a laboratory experiment was conducted, taking a commercially available digital camera and a digital video camera as the sensors and a model vehicle moving on rails as the robot. Two concrete blocks were placed at a certain distance away from the sensing system and serving as inspection targets. On still images taken by the camera, it was verified that the clear identification strongly depended on the short object distance, bright target surface, and quick shutter speed. Herein, the following condition presented a successful identification: 1-m object distance, 2300-lx illuminance, F2.8 aperture, 1/250-s shutter speed, 4608×3456 image resolution, and theoretical space resolution 0.09 mm/pixel. Longer object distance, faster moving speed, darker object surface and poorer theoretical space resolution would decrease the identification level. In videos taken by the digital video camera, it was verified that an object distance as short as 0.17 m could provide a high quality video from which the crack could be successfully identified. Those observations provided a useful basis for further development of the robot sensing system.

Peer-review under responsibility of the organizing committee of the 6th APWSHM

Keywords: bridge inspection; crack identification; image-based inspection; robot sensing system.

1. Introduction

Many roadway and highway bridges have been suffering from aging and deterioration problems, in carrying increasing vehicle loadings and facing various natural disasters such as earthquakes and typhoons. Current bridge inspections heavily rely on visual inspections [1], which are performed by trained inspectors using their vision, touch, and sometimes hearing to evaluate the bridge conditions. The visual inspection works are known to be time and labor consuming, limited to detecting visible damage, and usually produce large variations in the inspection results [2].

To inspect the bridges more efficiently and accurately, the Japanese government launched a series of national projects aiming to develop various innovative robotic inspection systems for aiding (but not replacing) the conventional visual inspections. One of the systems is designed to employ an autonomous mobile robot equipped with various sensing modules and therefore would

* Corresponding author. Tel.: +81-75-383-3421; fax: +81-75-383-3420.
E-mail address: kim.chulwoo.5u@kyoto-u.ac.jp

Peer-review under responsibility of the organizing committee of the 6th APWSHM
doi:10.1016/j.proeng.2017.04.456

have the following advantage: acquiring information of remote or even human-inaccessible targets; no traffic restriction required; labor saving and efficiency.

This study is devoted to developing the sensing modules compatible with the mobile robotic inspection system. One type of sensing modules is of image type, designed to take photos or videos of the target, from which defects like surface cracks could be identified. To investigate the feasibility of the image-type sensing modules, a laboratory experiment was conducted, taking a commercially available digital camera and a digital video camera as the sensors and a model vehicle moving on rails as the robot. This paper first provides an overall introduction to the experiment setup, then summarizes the outcomes of the experiment, and evaluates the feasibility of the proposed sensing modules and investigates the following factors: object distance, moving speed, object surface conditions including brightness and cleanliness, image resolution and theoretical space resolution.

2. Experiment Setup

2.1. Overall setup

The layout of the experiment is shown in Fig. 1. In the experiment, a commercially available digital camera and a digital video camera were taken as the sensors and a model vehicle moving on rails as the robot. The digital camera and digital video camera were installed on the model vehicle and operated by a remote controller. Two concrete blocks were placed at a certain distance away from the sensing system and serving as inspection targets; both blocks were covered with surface cracks but one was clean and the other has dirt on its surface. During the vehicle’s movement, the equipped camera or video camera took photos or videos of the target concrete blocks. Those photos and videos were then evaluated if surface cracks were clearly identified. Several factors were considered herein: the object distance, vehicle speed, illuminance of the object surface, aperture and shutter speed.

2.2. Digital camera and digital video camera

The digital camera used in this experiment is of OM-D E-M1 model (Olympus Co.) [3], equipped with a M.Zuiko ED12-40 mm F2.8 PRO lens [4](see Fig. 2(a)), and the digital video camera is of UCAM-DLK130TBK model (ELECOM Co.) [5] (see Fig. 2(b)). The former was planned to serve in a rough condition scanning, which would take place at the early stage of inspection. According to the present design, the rough condition scanning would be conducted at a further location and therefore ask for sensing modules capable of higher-resolution images. OM-D E-M1 camera was one of the candidates thanks to its 4608 $\times$3456-pixels high image resolution. The latter was planned to serve in a close inspection, which would take place at the later stage of inspection, once the rough scanning identifies some suspect defects. The close inspection would take place on a robotic arm, which posed a strict weight limitation and asked for a video stream recording. UCAM-DLK130TBK video camera was light enough and capable of videos up to 1280$\times$1024 pixels.

The selection of the above camera and video camera were dominated by a trade-off between the following requirements.

- The minimum crack width to be identified. Requested by the Guidelines for Bridge Regular Inspections, Japan, at least a crack of 0.1 mm in width should be successfully identified in a regular inspection. This requirement asked for a higher image resolution and therefore a higher-specification camera.
- The weight limitation on the robot. According to the current design, 1 kg would be the maximum loading that the robot arm could support. This loading limitation restricted the specifications of a camera, in viewing of the fact that generally a camera having higher specification is heavier under the same production level.

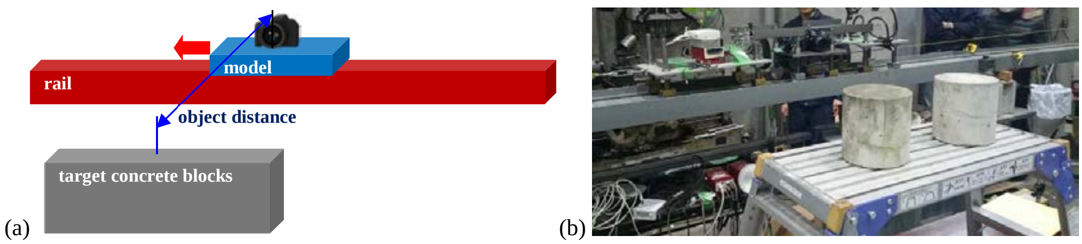


Fig. 1. Experiment setup: (a) schematic diagram; (b) photo.

(a) (b)

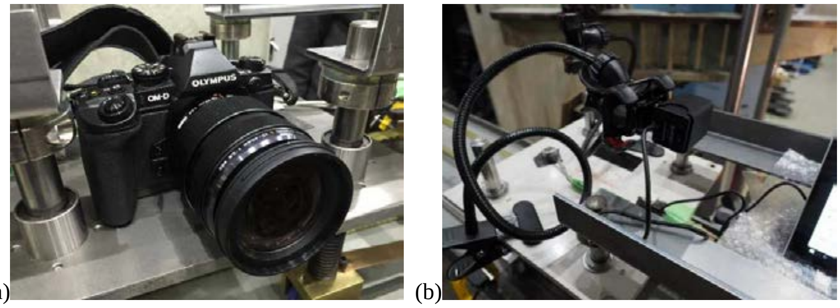


Fig. 2. (a) The camera and (b) video camera installed on the model vehicle.

(a) (b) (c)

Fig. 3. Target cracks: (a) clean target surface; (b) dirty target surface; (c) closer look with a width gauge. (red circles mark the location of 0.1-mm cracks)

2.3. Target concrete blocks and surface cracks

Two concrete blocks, serving as inspection targets, were placed at a certain distance away from the sensing system (see Fig. 1); both blocks were covered with surface cracks but one was clean and the other was dirty on surface, as shown in Figs. 3(a) and (b). The target width was 0.1 mm, as mentioned above. Those target surface cracks are also marked in Figs. 3(a) and (b), while a closer look of one crack along with a crack gauge is presented in Fig. 3(c).

2.4. Investigated factors and their combinations

2.4.1. Object distance

For the object distance, it is known that the closer the camera to the object, the higher the resolution can be expected. However, for real applications, too close the distance is impractical. For this reason, we first consider a theoretical maximum distance that could give a sufficient space resolution to identify a 0.1-mm crack. This space resolution is different from the image resolution; it is measured by the corresponding width on the target to one pixel on the photo. For an example, a 0.1 mm/pixel space resolution indicates that one pixel on the photo corresponds to 0.1 mm on the target. To identify a 0.1-mm crack, it is essentially required that the resolution is higher than 0.1 mm/pixel.

Provided that the OM-D E-M1 camera's angle of view is 24.4° horizontally and 18.5° vertically when the focal length is 40 mm. When the 4608×3456 pixel image resolution is set, the angle per pixel can be calculated as 0.0054° horizontally and 0.0053° vertically. Accordingly, to provide a sufficient resolution up to 0.1 mm/pixel, the maximum object distance can be calculated as

$$\text{Horizontally: } 0.001/\tan 0.0054° = 1.06 \text{ m} \tag{1}$$

$$\text{Vertically: } 0.001/\tan 0.0053° = 1.08 \text{ m} \tag{2}$$

Let us take an integer on conservative side, i.e. 1 m. To provide a comparison, 3 m object distance was also introduced.

The same logic also applied to the UCAM-DLK130TBK video recorder. Provided that its angle of view is 43° horizontally and 33° vertically and known that its image resolution is 1280×1024 pixels, the angle per pixel can be calculated as 0.0034° horizontally and 0.0032° vertically. To provide a sufficient resolution to identify a 0.1-mm crack, the maximum object distance can be calculated as

$$\text{Horizontally: } 0.001/\tan 0.0034° = 0.17 \text{ m} \tag{3}$$

$$\text{Vertically: } 0.001/\tan 0.0032° = 0.18 \text{ m} \quad (4)$$

Although the 0.17-m object distance would be rather impractical, it was still tested herein for verifying the theoretical value. Besides that, two more practical distances were tested: 0.5 and 1 m. Surely their theoretical resolution (calculated to 0.29 and 0.59 mm/pixel) would be insufficient to identify a 0.1 mm width, but how the photos taken in those practical distances would perform was also of our great interest.

2.4.2. Robot's moving speed

The design moving speed for the robot was 10 m/min, so this is the first choice of the moving speed to test in this study. In addition to that, 20 and 30 m/min were also tested for providing a clue that how the photos perform under a higher moving speed. If they worked fine, the design moving speed could be raised to save inspection time.

Table 1. Test cases and their conditions.

Camera	Case	Distance [m]	Speed [m/min]	Image type	Resolution	Brightness	Aperture & Shutter	space resolution [mm/pix]	Test runs
OM-D	1	1	10; 20; 30	still image	4608×3456	Bright; Dark	F2.8, 1/50 s F2.8, 1/250 s	0.09	12
	2	3	10; 20; 30	still image	4608×3456	Bright; Dark	F2.8, 1/50 s F2.8, 1/250 s	0.28	12
	3	0.6	10; Stationary	video	1280×720	Bright	--	0.27	4
UCAM-DLK130TBK	4	0.17	Stationary	video	1280×1024	Bright	--	0.10	2
	5	0.50	10	video	1280×1024	Bright; Dark	--	0.29	4
	6	1	10; Stationary	video	1280×1024	Bright; Dark	--	0.59	8

Table 2. Test cases, conditions, and the evaluation of results for still images.

Case No.	Distance [m]	Speed [m/min]	Illuminance [lx]	Aperture & Shutter	Space resolution [mm/pix]	Evaluation * (clean/dirty)
1-1-1	1	9.1	2300	F2.8, 1/50 s	0.09	B/B
1-1-2	1	9.1	2300	F2.8, 1/250 s	0.09	A/A
1-2-1	1	9.1	90	F2.8, 1/50 s	0.09	B/B
1-2-2	1	9.1	90	F2.8, 1/250 s	0.09	C/D
1-3-1	1	18.9	2300	F2.8, 1/50 s	0.09	D/D
1-3-2	1	18.9	2300	F2.8, 1/250 s	0.09	A/A
1-4-1	1	18.9	90	F2.8, 1/50 s	0.09	C/C
1-4-2	1	18.9	90	F2.8, 1/250 s	0.09	C/D
1-5-1	1	28.9	2300	F2.8, 1/50 s	0.09	D/D
1-5-2	1	28.9	2300	F2.8, 1/250 s	0.09	A/A
1-6-1	1	28.9	90	F2.8, 1/50 s	0.09	D/D
1-6-2	1	28.9	90	F2.8, 1/250 s	0.09	C/D
2-1-1	3	9.1	420	F2.8, 1/50 s	0.28	C/D
2-1-2	3	9.1	420	F2.8, 1/250 s	0.28	D/D
2-2-1	3	9.1	135	F2.8, 1/50 s	0.28	D/D
2-2-2	3	9.1	135	F2.8, 1/250 s	0.28	D/D
2-3-1	3	18.9	420	F2.8, 1/50 s	0.28	D/D
2-4-1	3	18.9	135	F2.8, 1/50 s	0.28	D/D
2-5-1	3	28.9	420	F2.8, 1/50 s	0.28	D/D
2-5-2	3	28.9	420	F2.8, 1/250 s	0.28	D/D
2-6-1	3	28.9	135	F2.8, 1/50 s	0.28	D/D
2-6-2	3	28.9	135	F2.8, 1/250 s	0.28	D/D

Note. * Evaluation A: clear identification of 0.1 mm cracks; B: vague identification of 0.1 mm cracks;
C: failed identification of 0.1 mm cracks but successful identification of wider cracks; D: failed identification of any crack.

2.4.3. Illuminance

Considering that the inspection works are often conducted under bridge decks, inside box girders, or some places in lack of light, the sensing system is expected to work well enough in dark environment. For this reason, both bright and dark environment were tested. The brightness of an object is commonly measured by illuminance in lx.

2.4.4. Aperture and shutter speed

In facing the dark environment, it would be preferable to open up the aperture as wide as possible to capture as much light as possible in one shot. Herein the aperture was kept F2.8 for all cases. As for the shutter speed, a faster speed, 1/250 s, and a slower speed, 1/50 s, was tested and compared.

2.4.5. Their combinations

Test cases and the combination of the above factors are listed in Table 1.

3. Results and Discussion

Let the model vehicle move along the rails and the camera or video camera on the vehicle take photos or videos of the target concrete blocks. Those photos and videos were then evaluated if target surface cracks were clearly identifiable. Evaluations along with the test conditions are summarized in Table 2 for still images and in Table 3 for videos. The evaluation was made visually and classified into four levels: "A" indicates a clear identification of 0.1 mm cracks, applicable when the 0.1 mm cracks clearly presented on the image (see Fig. 4(a) for a typical example); "B" indicates a vague identification of 0.1 mm cracks, applicable when the 0.1 mm cracks blurred on the image but the their existence still identifiable (see Fig. 4(b)); "C" indicates a failed identification of 0.1 mm cracks but successful identification of wider cracks (see Fig. 4(c)); "D" indicates a failed identification to any crack (see Fig. 4(d)).

3.1. Still images

Let us first investigate the effect of the surface cleanliness condition. It seems that there was little difference between the identification levels in the cases with clean and dirty surfaces in this experiment. It is known that the surface condition would vary greatly in different inspection locations, this observation might apply to the surface conditions similar to those considered in this study and surely a comprehensive investigation into the other patterns of surface condition would be helpful to support the present technique.

In the still-image cases, the clear identification strongly depended on the short object distance, bright target surface, and quick shutter speed. In this experiment, the cases with 1-m object distance, 2300-lx illuminance and 1/250-s shutter speed provided level A photos, despite of the moving speed being 9.1 (Case 1-1-2), 18.9 (Case 1-3-2), or 28.9 m/s (Case 1-5-2) and the surface being clear or dirty.

As the object distance increased, the identification level decreased. It can be seen that as the object distance increased from 1 m to 3 m, the identification level dropped dramatically. Almost all the cases with 3-m object distance (Cases 2-1-1 to 2-6-2) failed to identify any crack, i.e. a level D identification. The reason is rather obvious:

- As the object distance increased, the object projected on the digital imaging sensors in a smaller area and therefore decreased the space resolution. In this experiment, the theoretical space resolution decreased from 0.09 mm/pixel to 0.28 mm/pixel (Table 2); the latter was theoretically difficult to identify a 0.1-mm crack.
- As the object distance increased, implying the object were further from the light sources in our setup, the target surface became darker and therefore decreased the identification level (the factor of target surface brightness would be discussed in the next paragraph). It can be observed that the illuminance of the target surface dropped to 420 lx or smaller as the object distance increased to 3 m.

In viewing that almost all the cases with 3-m object distance failed to identify any crack and provided limited meaningful information, these cases were not taken into further investigation below. It is noteworthy that the test results on the space resolution were comparable with the theoretical investigations described in section 2.4.1.

As the target surface became darker, the identification level decreased. For example, when the illuminance decreased from 2300 lx in Case 1-1-2 to 90 lx in Case 1-2-2 (the other factors kept identical), the identification level decreased from A to C or D (clean or dirty surface); similar observation also applied to the case matches 1-3-2 vs. 1-4-2 and 1-5-2 vs. 1-6-2.

As the vehicle moved faster, the identification level decreased. The comparison of Cases 1-2-1, 1-4-1, and 1-6-1 provided a good example. As the vehicle speed increased from 9.1 m/s to 18.9 m/s and 28.9 m/s and the other factors were kept identical, the identification level decreased from B to C and D. The case match 1-1-1, 1-3-1, and 1-5-1 were also a good example: as the vehicle speed increased in the same pattern, the identification level decreased from B to D again.

As shutter speed was set slower, the identification level decreased. For example, as the shutter speed decreased from 1/250 s in Case 1-1-2 to 1/50 s in Case 1-1-1, the identification level decreased from A to B. Similar observations also applied to other case matches, such as 1-3-1 vs. 1-3-2 and 1-5-1 vs. 1-5-2.

It is believed that there should be some formula or criteria that could quantitatively describe the relation between those factors. Those formula and criteria would be helpful in making decision on those important factors under various potential inspection environment, in figuring out the applicable range, and even expanding the range. At this stage, this formulation is still under investigation.

Table 3. Test cases, conditions, and the evaluation of results for videos.

Case No.	Camera	Distance [m]	Speed [m/min]	Illuminance [lx]	Resolution	Condition*	Space resolution [mm/pix]	Evaluation** (clean/dirty)
3-1	OM-D	0.6	0	3100	1280×720	I	0.27	B/B
3-2		0.6	9.1	3100	1280×720	I	0.27	A/A
4-1	UCAM-DLK130TBK	0.17	0	450	1280×1024	II	0.10	B/B
5-1		0.50	9.1	450	1280×1024	II	0.29	C/D
5-2		0.50	9.1	90	1280×1024	III	0.29	B/B
6-1		1	0	900	1280×1024	II	0.59	C/D
6-2		1	0	90	1280×1024	III	0.59	B/B
6-3		1	9.1	900	1280×1024	II	0.59	C/D
6-4		1	9.1	90	1280×1024	III	0.59	B/B

Note. * Condition I: aperture F2.8;
II: color space YUY2, frame rate 30 fps, exposure -10, brightness -6, contrast 4, saturation 6, sharpness 8, white balance 6500;
III: color space YUY2, frame rate 30 fps, exposure -5, brightness 0, contrast 20, saturation 6, sharpness 8, white balance 6500.
** Evaluation shares the same definition as in Table 2.

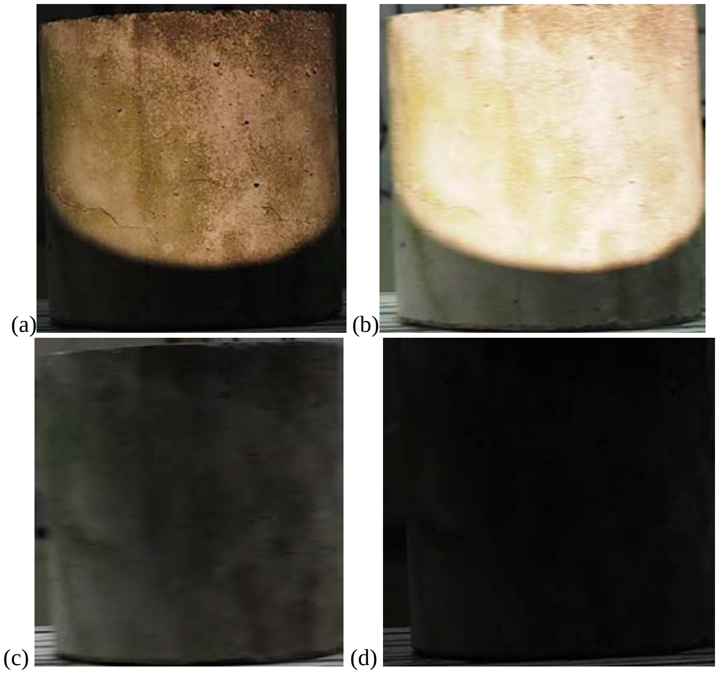


Fig. 4. Typical evaluation: (a) A (Case 1-1-2); (b) B (Case 1-1-1); (c) C (Case 1-4-1); (d) D (Case 1-4-2).

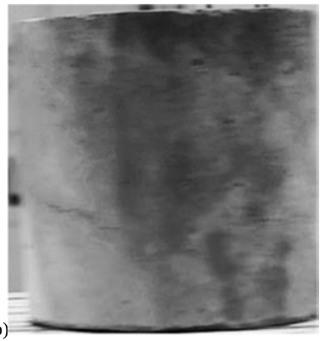
(a)  (b) 

Fig. 5. Typical evaluation: (a) Case 1-4-1; (b) contrast adjusted Case 1-4-1.

3.2. Videos

The identification level A in Case 4-1 successfully verifies our prediction: an object distance as short as 0.17 m, with a sufficient theoretical space resolution up to 0.1 mm/pixel, would provide a high quality video from which the 0.1 mm crack could be successfully identified. From the other cases, the effect of some factors can be observed. As object distance increased, the theoretical space resolution decreased and accordingly the identification level decreased as expected. As the illuminance on the surface decreased, the identification level decreased as well. Most of the observations agreed with those for still images as discussed in the previous section. However image processing techniques could improve the photo quality and enhance the crack identification ability. The image in Case 4-1-1 after adjusting the image color and tone is shown in Fig. 5 (b) with original one (Fig. 5(a)), which demonstrates possibility of improving the image quality so as to improve the crack identifiabilty. Other advanced image processing techniques, like the Phase stretch transform [6] and super-resolution technology [7], would be promising methods to improve the crack identifiabilty but a comprehensive study is still ongoing.

4. Concluding Remarks

A laboratory experiment was conducted to investigate the feasibility of the image-type sensing modules to be embedded on a developing robotic inspection system. In the experiment, a commercially available digital camera and a digital video camera was taken as the sensing modules and a model vehicle moving on rails were taken as the robot. Let the model vehicle move along the rails and the camera or video camera on the vehicle take photos or videos of target concrete blocks. Those photos and videos were then visually evaluated if target surface cracks were identifiable.

On still images taken by the digital camera, it was verified that the clear identification strongly depended on the short object distance, bright target surface, and quick shutter speed. In this study, the following condition presented a successful identification of the target 0.1 mm crack: 1-m object distance, 2300-lx illuminance, F2.8 aperture, 1/250-s shutter speed. 4608×3456 image resolution, and theoretical space resolution 0.09 mm/pixel (dependent on the object distance and image resolution). The following condition would decrease the identification level: longer object distance and faster moving speed, darker object surface (dependent on the object distance in some cases) and poorer theoretical space resolution. On other hand, the clean and dirty object surfaces presented little difference in identification level.

In videos taken by the digital video camera, it was verified that an object distance as short as 0.17 m, with a sufficient theoretical space resolution up to 0.1 mm/pixel, could provide a high quality video from which the 0.1 mm crack could be successfully identified. However, the very short object distance seemed impractical in real applications, which is a critical issue under investigation.

The test results on the space resolution were comparable with the theoretical investigation, which encourages the use of theoretical space resolution on the selection of the camera for a specific need of sensing distance from the camera and target structures and accuracy.

Based on the above qualitative observations, it is suggested to construct a quantitative formulation and evaluation constructing the relation between the key factors. In addition, in acknowledging that there is definitely a limitation on the digital devices' physical performance, a study is ongoing to develop effective image processing techniques that can improve the photo quality and enhance the crack identification ability.

Acknowledgements

This work was supported, in part, by Council for Science, Technology and Innovation, “Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management”. (funding agency: NEDO) The graduate students GOI, Yoshinao and KAWABE, Daigo of Kyoto University helped in conducting the laboratory experiments. Their help is sincerely acknowledged.

References

[1] Ministry of Land, Infrastructure, Transpor and Tourism, *Guidelines for Bridge Regular Inspections*, 2014. http://www.mlit.go.jp/road/ir/ir-council/pdf/yobo3_1_6.pdf , accessed 8th Aug. 2016. (Japanese)

[2] P. Chupanit and C. Phromsorn, The Importance of Bridge Health Monitoring, *International Scholarly and Scientific Research & Innovation* 6(6) (2012), 389-392.

[3] http://www.getolympus.com/us/en/digitalcameras/omd/e-m1.html , accessed 8th Aug. 2016.

[4] http://www.getolympus.com/us/en/m-zuiko-digital-ed-12-40mm-f2-8-pro.html , accessed 8th Aug. 2016.

[5] http://www2.elecom.co.jp.e.gj.hp.transer.com/multimedia/pc-camera/ucam-dlk130t/ , accessed 8th Aug. 2016.

[6] Phase stretch transform – Wikipedia, https://en.wikipedia.org/wiki/Phase_stretch_transform, accessed 8th Aug. 2016.

[7] http://jpn.nec.com/ad/onlinetv/rd/srt_h.html , accessed 8th Aug. 2016.